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Cooling Energy Savings Potential of Light-Colored Roofs for Residential and Commercial Buildings in 11 U.S. Metropolitan Areas

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S. Gabersek, and L. Gartland

**Environmental Energy
Technologies Division**

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Abstract

Light-colored roofs reflect more sunlight than dark roofs, thus they keep buildings cooler and reduce air-conditioning demand. Typical roofs in the United States are dark, which creates a potential for saving energy and money by changing to reflective roofs. In this report, we make quantitative estimates of the impact of roof color by simulating prototypical buildings with light- and dark-colored roofs and calculating savings by taking the differences in annual cooling and heating energy use, and peak electricity demand. Monetary savings are calculated using local utility rates. Savings are estimated for 11 U.S. Metropolitan Statistical Areas (MSAs) in a variety of climates. We used the DOE-2 building energy simulation program for these calculations.

Estimates of savings for an entire MSA is obtained by scaling the savings for the prototypical buildings with the total air-conditioned space in each MSA. The largest potential for net annual energy cost savings were found in Phoenix ($37M [$34 per 1000ft^2 roof area of air-conditioned buildings]), followed by Los Angeles ($35M [$20]), Houston ($27M [$18]), Miami/Fort Lauderdale ($20M [$21]), Dallas/Fort Worth ($20M [$11]), New York City ($16M [$17]), Chicago ($10M [$9]), New Orleans ($9M [$17]), Atlanta ($9M [$10]), Washington, DC/Baltimore ($8M [$5]), and Philadelphia ($3M [$4]). The totals for all 11 MSAs were: total annual electricity savings, 2.6 terawatt hours (TWh); net energy savings, $194M and peak electricity demand savings, 1.7 gigawatt (GW). Six building types accounted for over 90% of the annual electricity and net energy savings: old residences were responsible for almost 55%, new residences 15%, and four other building types (old/new offices and old/new retail stores) together almost 25%. Extrapolating the savings from the 11 MSAs to the entire United States, we estimated annual electricity savings of about 10 TWh and a net savings of about $750M in annual energy payments. Peak electricity power reduction was estimated to be about 7 GW.

Executive Summary

The U.S. Environmental Protection Agency (EPA) sponsored this project to estimate potential energy and monetary savings resulting from the implementation of light-colored roofs on residential and commercial buildings in major U.S. metropolitan areas. Light-colored roofs reflect more sunlight than dark roofs, so they keep buildings cooler and reduce air-conditioning demand. Typically, rooftops in the United States are dark, and thus there is a potential for saving energy and money by changing to reflective roofs. Naturally, the expected savings are higher in southern, sunny, and cloudless climates. In this study, we make quantitative estimates of reduction in peak power demand and annual cooling electricity use that would result from increasing the reflectivity of the roofs. Since light-colored roofs also reflect heat in the winter, the estimates of annual electricity savings are a net value corrected for the increased wintertime energy use. Savings estimates only include **direct** reduction in building energy use and do not account for the **indirect** benefit that would also occur from the reduction in ambient temperature, i.e. a reduction in the heat island effect.

This analysis is based on simulations of building energy use, using the DOE-2 building energy simulation program. Our methodology starts with specifying 11 prototypical buildings:† single-family residential (old and new), office (old and new), retail store (old and new), school (primary and secondary), health (hospital and nursing home), and grocery store. Most prototypes are simulated with two heating systems: gas furnace and heat pumps. We then perform DOE-2 simulations of the prototypical buildings, with light and dark roofs, in a variety of climates and obtain estimates of the energy use for air conditioning and heating. Weather data for 11 U.S. Metropolitan Statistical Areas (MSAs) are used: Atlanta, Chicago, Los Angeles, Dallas/Fort Worth, Houston, Miami/Fort Lauderdale, New Orleans, New York City, Philadelphia, Phoenix, and Washington, DC/Baltimore. Cooling energy savings and heating energy penalties are then obtained by calculating the difference between the simulated energy use of the prototype buildings with light- and dark-colored roofs.

We proceed from the estimates of savings in individual buildings to the entire MSA, by calculating how much energy and money could be saved if the current building stock had its roofs changed from dark to light. This is done by scaling the simulated energy savings of the prototype buildings by the amount of air-conditioned space immediately beneath roofs in an entire MSA. For this, we use data in each MSA on the stock of commercial and residential buildings, the saturation of heating and cooling systems, the current roof reflectivities, and the local costs of electricity and gas.

The estimates of the direct savings are shown in **Table EX-1**. The largest potential for net annual dollar savings was found in Phoenix, $37 million ($37M), followed by Los Angeles ($35M), Houston ($27M), Miami/Fort Lauderdale ($20M), Dallas/Fort Worth ($20M), New York

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† In a multi-story building, only the top floor which is directly affected by the roof color is included.

City ($16M), Chicago ($10M), New Orleans ($9M), Atlanta ($9M), Washington, DC/Baltimore ($8M), and Philadelphia ($3M). The same quantities per $1000ft^2$ of roof area of air-conditioned buildings for each MSA are shown in **Table EX-2**. To illustrate the climate effect, the results are plotted in **Figures EX-1** to **EX-4**, superimposed on a map of the United States with contours of annual cooling hours for a typical residential building. The data per $1000ft^2$ of roof area reflect the effects of climate, whereas the MSA savings are strongly affected by the sizes of the populations.

The sum total for all 11 MSAs are: electricity savings, 2.6 terawatt hours (TWh) (200 kilowatt hours per $1000ft^2$ of roof area of air-conditioned buildings); natural gas deficit, 6.9 TBtu (5 therms per $1000ft^2$); net savings in energy bills, $194M ($15 per $1000ft^2$); and savings in peak demand 1.7 gigawatt (GW) (135 W per $1000ft^2$). Six building types account for over 90% of the annual electricity and net dollar savings: old residences more than 55%, new residences about 15%, and four other building types (old/new offices and old/new retail stores) together about 25%.

The results for the 11 MSAs are extrapolated to estimate the savings in the entire United States. This extrapolation is done first by scaling to the national population, and then by a method that accounts for the climatic variations of the savings. We find that the national savings are about four times the savings for the 11 MSAs: a decrease in annual direct electricity use by 9.3 to 11 TWh (about 3.0% of the national cooling electricity use in residential and commercial buildings), an increase in natural gas use by 25 to 28 GBtu (1.6%), decrease peak electrical demand by 6.2 to 7.2 GW (2.5%) (equivalent to 12 to 14 power plants each with a capacity of 0.5 GW), and a decrease in net energy bills for the rate-payers by $680M to $850M.

Table EX-1. Estimates of **metropolitan-scale** annual direct cooling electricity savings, annual natural gas penalty, net dollar savings, and peak electricity demand savings, resulting from application of light-colored roofing on residential and commercial buildings in 11 Metropolitan Statistical Areas. Net dollar savings are calculated using the local cost of electricity and gas. For example, in Phoenix, the average price of electricity and gas for commercial and residential consumers are: 1kWh costs $0.104; and 1MBtu $6.40.

Metropolitan Area	Residential Savings						Commercial Savings						Residential and Commercial Savings					
	elec		gas		**net**	peak	elec		gas		**net**	peak	elec		gas		**net**	peak
	(GWh)	(M$)	(GBtu)	(M$)	(M$)	(MW)	(GWh)	(M$)	(GBtu)	(M$)	(M$)	(MW)	(GWh)	(M$)	(GBtu)	(M$)	(M$)	(MW)
Atlanta	125	9.8	-349	-2.4	**7.4**	83	22	1.6	-55	-0.3	**1.3**	14	147	11.4	-404	-2.7	**8.7**	97
Chicago	100	11.2	-988	-5.4	**5.8**	89	84	7.0	-535	-2.7	**4.3**	56	183	18.2	-1523	-8.1	**10.1**	145
Los Angeles	210	20.6	-471	-2.9	**17.7**	218	209	18.6	-154	-0.9	**17.7**	102	419	39.2	-625	-3.8	**35.4**	320
Dallas / Ft Worth	241	18.6	-479	-2.8	**15.8**	175	71	4.5	-113	-0.5	**4.0**	36	312	23.1	-592	-3.3	**19.8**	211
Houston	243	22.6	-284	-1.7	**20.9**	127	79	6.0	-62	-0.3	**5.7**	30	322	28.6	-347	-2.0	**26.6**	156
Miami / Ft Lauderdale	221	17.9	-4	0.0	**17.9**	115	35	2.4	-3	0.0	**2.4**	11	256	20.3	-7	0.0	**20.3**	125
New Orleans	84	6.6	-107	-0.7	**5.9**	27	33	2.8	-28	-0.1	**2.7**	16	117	9.4	-135	-0.8	**8.6**	42
New York	35	5.6	-331	-2.7	**2.9**	56	131	16.5	-540	-3.3	**13.2**	95	166	22.1	-871	-6.0	**16.1**	151
Philadelphia	44	5.6	-954	-6.5	**-0.9**	108	47	5.5	-292	-1.8	**3.7**	49	91	11.1	-1246	-8.3	**2.8**	157
Phoenix	299	32.0	-74	-0.5	**31.5**	106	58	5.3	-31	-0.2	**5.1**	18	357	37.3	-105	-0.7	**36.6**	123
DC / Baltimore	182	13.1	-845	-7.0	**6.1**	183	45	3.2	-184	-1.1	**2.1**	31	227	16.3	-1029	-8.1	**8.2**	214
Total	1784	163.6	-4886	-32.6	**131.0**	1287	814	73.4	1997	11.2	**62.2**	458	2597	237.0	6884	43.8	**193.2**	1741

Table EX-2. Estimates of annual direct savings and penalties **per 1000 ft^2 of roof area of air-conditioned buildings** resulting from application of light-colored roofing on residential and commercial buildings in 11 Metropolitan Statistical Areas. Net dollar savings are calculated using the local cost of electricity and gas. For example, in Phoenix, the average price of electricity and gas for commercial and residential consumers are: 1kWh costs $0.104; and 1 therm = 0.1MBtu costs $0.64.

Metropolitan Area	Residential Savings				Commercial Savings				Residential and Commercial Savings			
	elec (kWh)	gas (therms)	**net ($)**	peak (W)	elec (kWh)	gas (therms)	**net ($)**	peak (W)	elec (kWh)	gas (therms)	**net ($)**	peak (W)
Atlanta	153	-4	**10**	102	239	-6	**11**	152	162	-4	**10**	107
Chicago	131	-13	**8**	116	228	-15	**11**	152	162	-13	**9**	128
Los Angeles	182	-4	**16**	189	350	-3	**30**	171	239	-4	**20**	183
Dallas / Ft Worth	166	-3	**11**	121	224	-4	**13**	114	176	-3	**11**	119
Houston	198	-2	**17**	103	261	-2	**20**	99	211	-2	**18**	102
Miami / Ft Lauderdale	259	0	**21**	135	340	0	**19**	107	267	0	**21**	131
New Orleans	199	-3	**14**	64	287	-2	**26**	139	218	-3	**17**	78
New York	104	-10	**9**	166	211	-9	**21**	153	173	-9	**17**	158
Philadelphia	81	-18	**-2**	199	232	-14	**20**	241	122	-17	**4**	211
Phoenix	314	-1	**34**	111	409	-2	**35**	127	327	-1	**34**	113
DC / Baltimore	137	-6	**5**	138	221	-9	**10**	152	148	-7	**5**	140

Figure EX-1: Annual Net Dollar Savings for 11 Metropolitan Areas

Net $ Savings = $ Cooling Energy Savings – $ Heating Energy Penalties

The contour map shows simulated annual cooling hours for a typical house (Source: Kelly & Parken 1978).

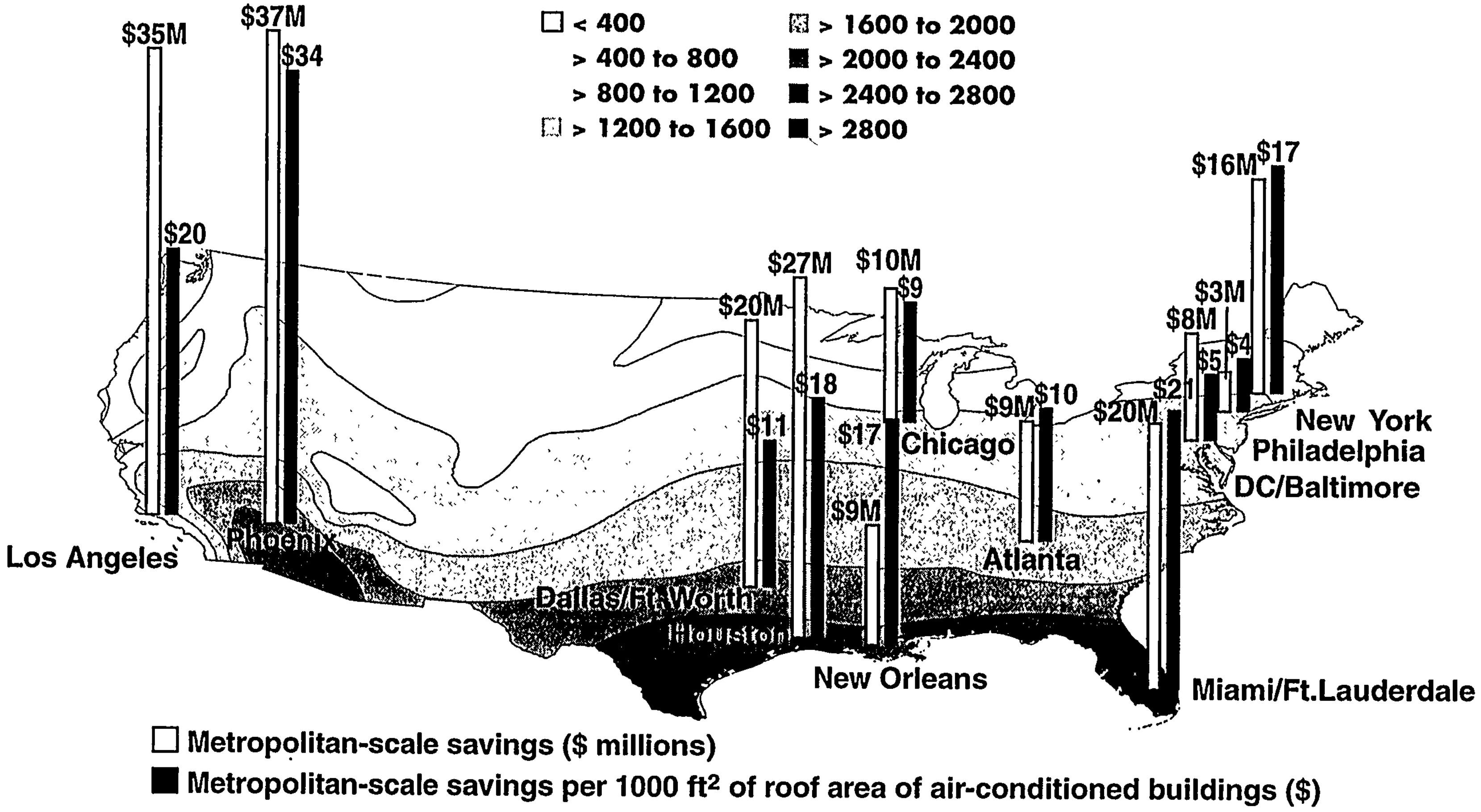


Figure EX-2: Annual Cooling-Electricity Savings for 11 Metropolitan Areas

The contour map shows simulated annual cooling hours for a typical house (Source: Kelly & Parken 1978).

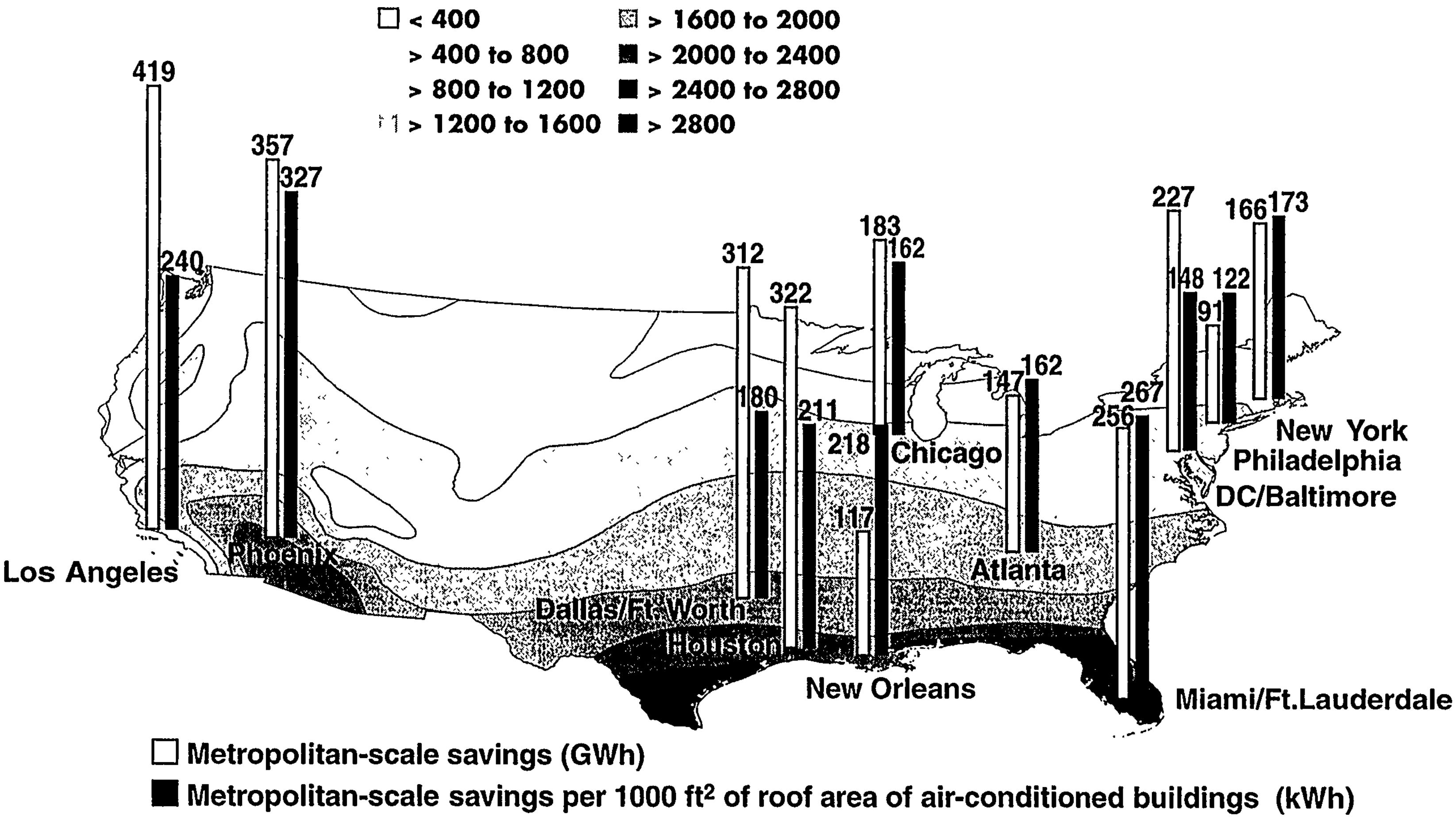


Figure EX-3: Annual Heating Energy Penalties for 11 Metropolitan Areas

The contour map shows simulated annual cooling hours for a typical house (Source: Kelly & Parken 1978).

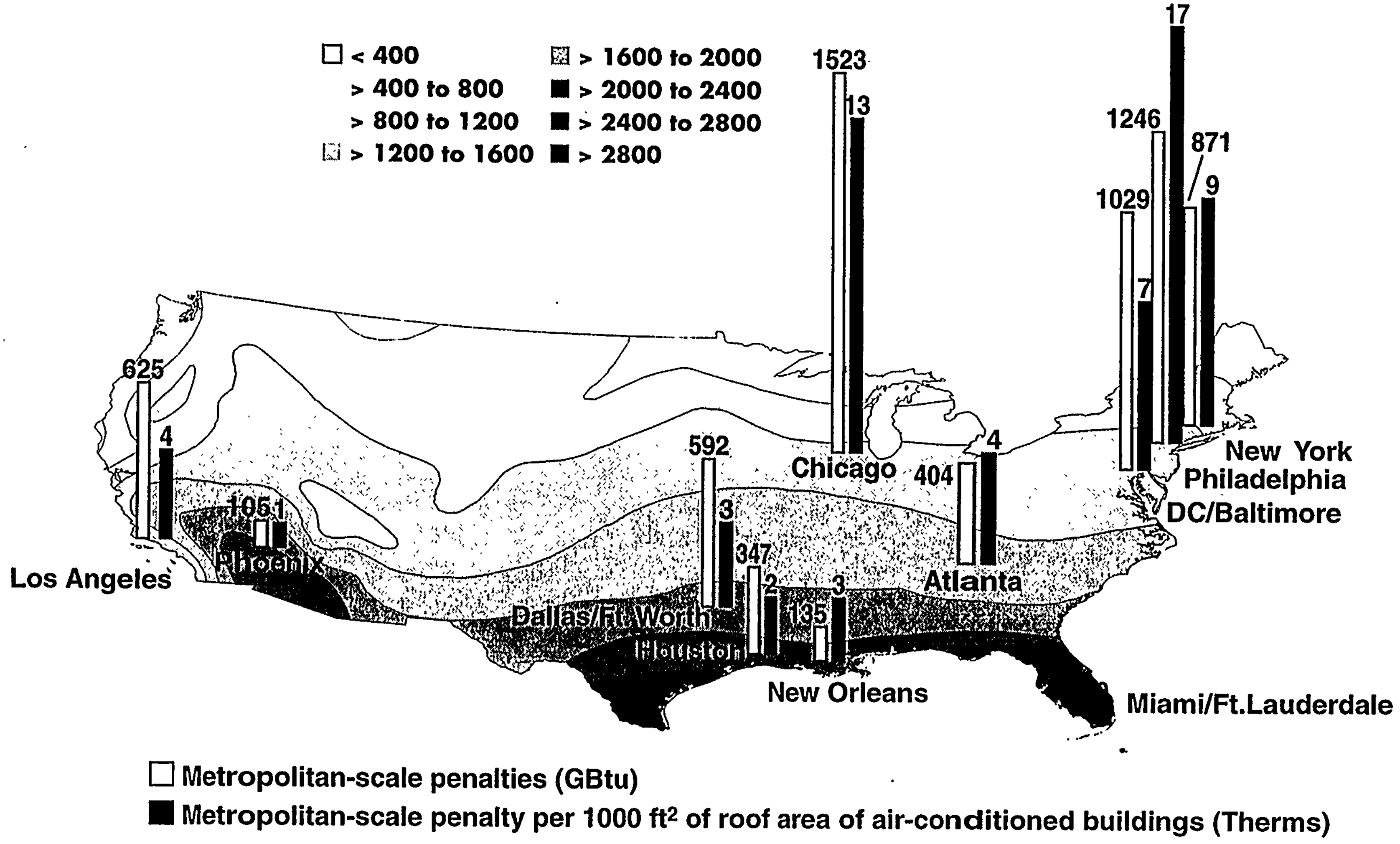
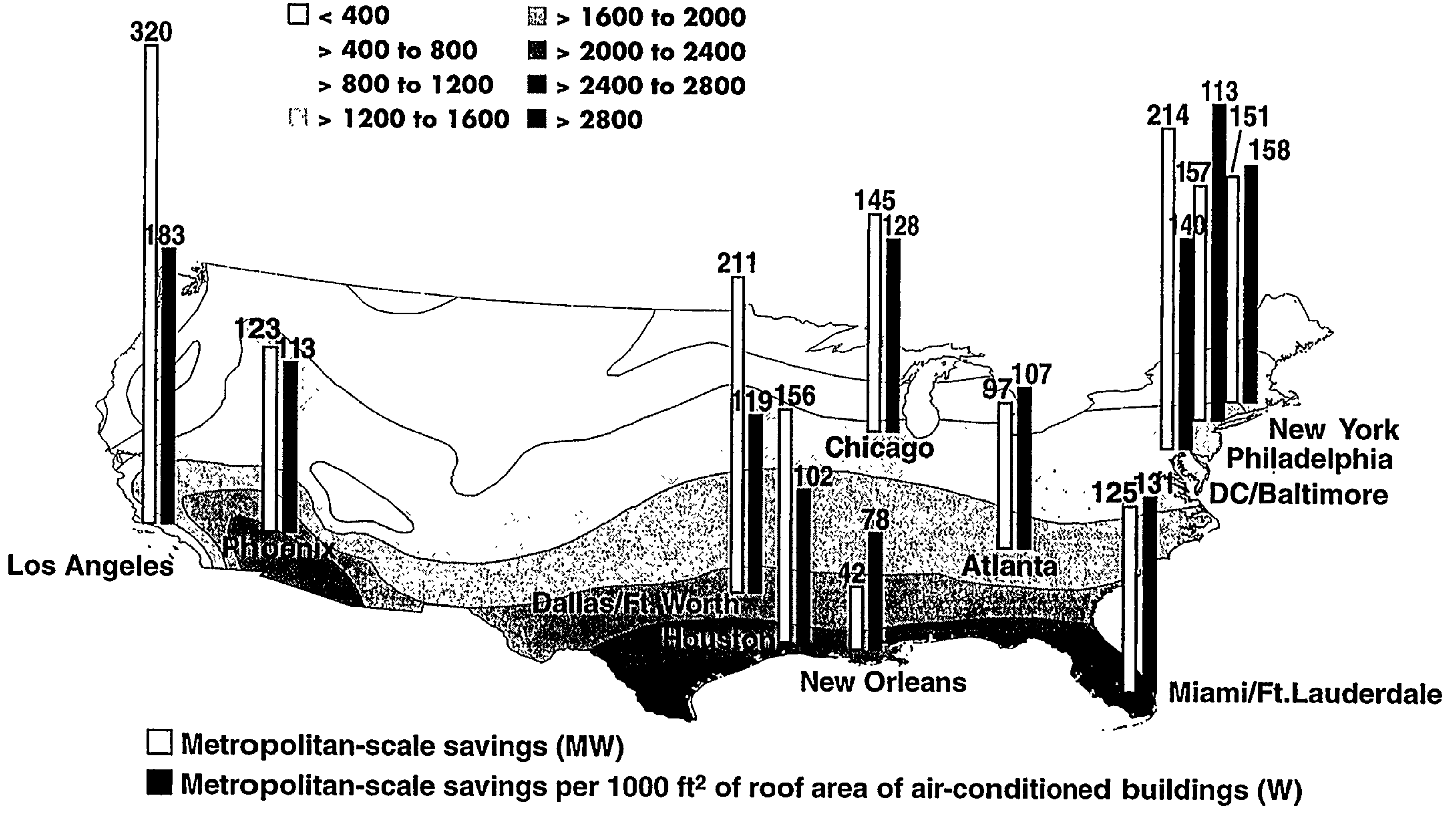


Figure EX-4: Peak-Cooling Electricity Demand Savings for 11 Metropolitan Areas

The contour map shows simulated annual cooling hours for a typical house (Source: Kelly & Parken 1978).



Chapter 1

Introduction

Background

The heat gain through a roof is a dominant component of the total cooling load of a single-story building. Roof loads are maximized when little or no insulation is present and the exterior surface is dark colored; i.e., when solar reflectance (albedo[1]) is low. Typically, rooftops in the United States are dark colored and in some areas roofs have little or no insulation. Thus, the potential exists for saving cooling energy, especially in hot and sunny climates. This concept is well known, as light-colored (high-albedo) roofing has historically been employed as a method to cool buildings naturally and increase human comfort in hot and sunny climates throughout the world. Sometimes a heating penalty is assessed when reflective roofing is applied, since less sunlight is absorbed by the roof during the heating season. However, in many locations and buildings the savings in cooling electricity dollars far exceed the penalty in heating gas dollars. The technology has been shown to be cost-effective, with less than a 1% additional cost when considering black versus white asphalt shingles or gravel (Bretz, et al., 1997).

The reflective-roofing strategy has been investigated through metering and simulations as a method to reduce electricity use in buildings, and decrease air temperature and air pollution in urban heat islands[2]. Electricity savings have been measured in several buildings in Sacramento, California (Akbari, et al., 1993a), where high-albedo coatings were applied to roofs. The reduction in cooling peak power was 30-40% and in cooling energy 40-50%. Daily air-conditioning electricity savings of 10-43% and utility coincident peak power saving of 12-38% were demonstrated with reflective-roof coatings in field tests of eight Florida homes (Parker, et al., 1995). The largest savings were found in a building without roof insulation and the least in one with R-19 insulation. Cooling electricity savings of 22% were measured in a Mississippi office building following the application of a light-colored roof coating (Boutwell, et al., 1986). Building energy simulations completed for the Los Angeles Basin (Taha, et al., 1996) show peak cooling demand savings of 20%-40% in residences and 5%-10% in offices resulting from an increase in roof albedo of 0.4.

Objective

The objective of this project was to develop a database. In which, we quantify building-scale and metropolitan-scale energy and monetary savings resulting from the application of light-colored roofing for several building types in 11 U.S. Metropolitan Statistical Areas (MSAs) with

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[1] Albedo is defined as the hemispherical reflectivity integrated over the solar spectrum.

[2] An urban heat island is defined as a large metropolitan area with an air temperature several degrees higher than the surrounding rural environment. A discussion of current urban heat island research can be found in Rosenfeld, et al., 1995.

significant heat island related problems; i.e., growing pollution, temperature, and electricity demand. The areas selected were: Atlanta, Chicago, Los Angeles, Dallas/Fort Worth, Houston, Miami/Fort Lauderdale, New Orleans, New York City, Philadelphia, Phoenix, and Washington DC/Baltimore. The buildings selected were: single-family residence (old and new), office (old and new), retail store (old and new), school (primary and secondary), health (hospital and nursing home), and grocery store. The domains of the 11 MSAs were defined by the U.S. Office and Management and Budget as either a Consolidated Metropolitan Statistical Area (CMSA) or Metropolitan Statistical Area (MSA). The 1990 population of each of these areas are listed in **Table 1-1**, which total almost 70 million or 28% of the entire U.S. population.

Table 1-1. 1990 populations of U.S. Consolidated Metropolitan Statistical Areas (CMSA) and Metropolitan Statistical Areas (MSA) for 11 urban heat island locations (Census, 1990). A CMSA is a collection of adjacent MSAs.

metropolitan statistical area	designation	population
Atlanta	MSA	2,833,511
Chicago	CMSA	8,065,633
Los Angeles	CMSA	14,531,529
Dallas/Fort Worth	CMSA	3,885,415
Houston	CMSA	3,711,043
Miami/Fort Lauderdale	CMSA	3,192,582
New Orleans	MSA	1,238,816
New York	CMSA	18,087,251
Philadelphia	CMSA	5,899,345
Phoenix	MSA	2,122,101
DC/Baltimore	CMSA	6,305,746
Total		69,872,972
United States		248,709,873

Methodology

The methodology used in obtaining these savings estimates is shown in **Figure 1-1** and is highlighted here. The average roof albedos for existing residential and commercial buildings were estimated from an analysis of digitized aerial photographs as described in *Chapter 2*, and in greater detail in *Appendix A*. These values were used to define roof albedo in building input files for DOE-2 energy-use simulations and to adjust the metropolitan-scale estimates for local variations in albedo.

Building-scale cooling and heating estimates resulted from using the DOE-2.1E building energy simulation program and are discussed in *Chapter 3*. Annual and peak electricity demand, and annual natural gas use were estimated for two roof albedo cases, 'base' and 'modified', for each building type and location. The average local price of electricity and gas were used to obtain building-scale net energy bill estimates. Building-scale energy savings were taken as the difference between the modified case and the base case. The entire building-scale data base and supplemental data are located in *Appendix B*.

Conditioned flat roof area was estimated for both residential and commercial buildings. Residential building stock were obtained from the American Housing Survey (AHS) and commercial stock from the Commercial Building Energy Consumption Survey (CBECS). These data, shown in *Appendix C*, were analyzed as described in *Chapter 4* to determine residential and commercial conditioned flat roof area. The estimates were used to scale building-scale energy and monetary savings to the metropolitan-scale domain.

Metropolitan-scale HVAC annual electricity and net energy savings, peak electricity demand savings, and annual natural gas deficit were estimated, as discussed in *Chapter 5*, as the product of the conditioned flat roof area, the building-scale energy and monetary savings, and the local variation in base roof albedo. The entire metropolitan-scale data base and supplemental data are located in *Appendix D*. Also, the base use and savings were extrapolated to obtain national estimates.

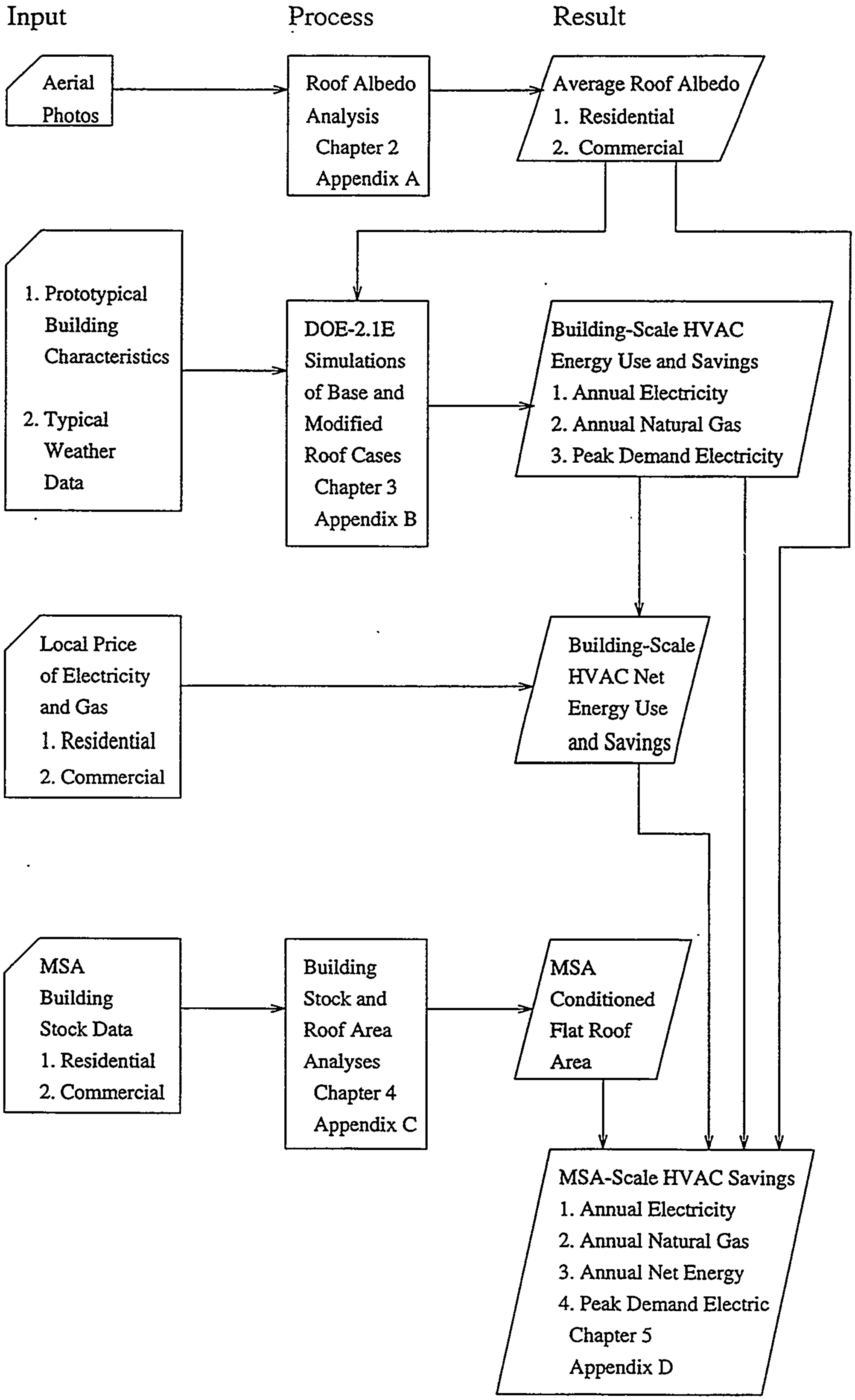

Figure 1-1. Methodology to obtain building and metropolitan-scale energy savings.

Chapter 2

Roof Albedo

We used digitized aerial photographs to determine the average roof albedo for existing residential and commercial buildings. The average metropolitan-scale roof albedo was used to define roof albedo in building input files for DOE-2 energy-use simulations (*Chapter 3*), and to adjust the metropolitan-scale results for local variations in albedo (*Chapter 5*). The analysis and results are discussed briefly here and in greater detail in *Appendix A*.

Base case roof albedos were estimated for residential and commercial buildings from digitized photographs taken over Atlanta, Philadelphia, and Washington DC (photographs of the other areas were unavailable). The analysis of the photographs revealed that the average residential and commercial building rooftop albedos were within 0.02 (scale 0-1) of each other, and that rooftops were lightest in Atlanta and darkest in Philadelphia; i.e., roofs get darker moving south to north. As shown in **Table 2-1**, the average albedo of all buildings was 0.31 in Atlanta, 0.25 in Washington DC, and 0.19 in Philadelphia. The average for all buildings and locations was 0.25, which was the value used as input to building energy simulation models. We consider the value 0.25 high and think it should be closer to 0.15, since a typical new black asphalt shingle has a measured albedo of 0.05, dark brown 0.08, green 0.19, and white of 0.25 (Berdahl and Bretz, 1995).

The values in Table 2-1 were defined as the local base albedo and were used to adjust for local variations, where the base albedo was not 0.25, as they were in the building energy simulations. This is an application of the observation that energy and monetary savings follow a linear relationship with changes in roof albedo. We assumed all Southern locations (Los Angeles, Dallas/Fort Worth, Houston, Miami/Fort Lauderdale, New Orleans, and Phoenix) had the same albedo as Atlanta. Likewise, we assumed the Northern locations of Chicago and New York City had the same albedo as Philadelphia.

Table 2-1. Average roof albedo for existing residential and commercial buildings from analysis of digitized aerial photographs taken over Atlanta, Washington DC, and Philadelphia.

metropolitan area	average roof albedo		
	residential	commercial	total
Atlanta	0.30	0.32	0.31
Washington DC	0.25	0.25	0.25
Philadelphia	0.20	0.18	0.19
average	0.25	0.25	0.25

Chapter 3

Building-Scale HVAC Energy and Monetary Base Use and Savings

Building-scale HVAC electricity and natural gas use were estimated using the DOE-2.1E building energy simulation program (BESG, 1990). DOE-2 requires 'typical' annual hourly weather data for each location and prototypical building characteristics as input. The weather tapes that represented each MSA are shown in **Table B-1** with typical weather data.

DOE-2 Building Prototypes

Prototypical building characteristics were developed from construction, internal load, and HVAC system characteristics summarized in **Table 3-1** and described in detail in **Tables B-3** through **B-18** for single-family residential and commercial types (office, retail store, primary and secondary schools, hospital, nursing home, and grocery store) types. The residential, office, and retail store buildings were split into old (pre-1980) and new (1980 and later) vintages and modeled with both gas furnaces and electric heat pumps.

The HVAC system components (supply fan, packaged air conditioner / heat pump, and gas furnace; chiller, cooling tower, and boiler for hospital) were sized by allowing DOE-2 to select base case default capacities for each building type and location. Component sizes were then selected based on engineering judgement and used in the building prototypes for DOE-2 modeling in both the base and modified roof cases, and are displayed in Tables B-3 through B-18. In some cases, it was found that light-colored roofing may allow for the air conditioner to be down-sized.

Roof/Attic/Ceiling Model

The roof/attic/ceiling structure is difficult to model in DOE-2, because it is an unconditioned space with significant thermal mass, experiences high temperature swings, and is prone to irregular ventilation rates. It can be modeled as a single-layered construction or as an unconditioned zone. The single-layered construction model has the benefit of incorporating the insulation thermal mass, where the unconditioned zone model can account for variation in attic ventilation rates. However, the effective thermal resistance of a naturally ventilated attic can be modeled as constant (ASHRAE, 1989). Also, regarding the single-layered model, errors are significant only in very poorly insulated or power-ventilated attics (Huang, et al., 1987). We chose the single-layered construction model, since we were interested to include the insulation thermal mass, and our buildings were fitted with either R-11 or R-19 insulation and did not have power ventilation.

The layers of the roof construction for all buildings[3] were: 1/4" asphalt shingles, over 1/2" of plywood, over an effective attic resistance, over insulation (R-11 for old vintages or R-19 for new), over 1/2" of drywall. The roof exterior had an infrared emittance of 0.91 and either a base

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[3] The exception was the hospital, which also had a concrete deck.

Table 3-1. Prototypical building HVAC system and construction characteristics.

Building Prototype		HVAC[a]	Insulation		Floor Area (ft^2)	Floors	Flat Roof Area[b] (ft^2)
		System Type	Roof	Wall			
Residence	Old	Gas Furnace & Heat Pump	R-11	R-7	1500	1	1500
	New	Gas Furnace & Heat Pump	R-19	R-11			
Office	Old	Gas Furnace & Heat Pump	R-11	R-7	4900	1	4900
	New	Gas Furnace & Heat Pump	R-19	R-11			
Retail Store	Old	Gas Furnace & Heat Pump	R-11	R-7	8100	1	8100
	New	Gas Furnace & Heat Pump	R-19	R-11			
School	Primary	Gas Furnace	R-11	R-7	35000	1	35000
	Secondary				100000	3	57000
Health	Hospital	Gas Boiler	R-11	R-7	132000	7	18900
	Nursing Home	Gas Furnace			38400	1	38400
Grocery Store		Gas Furnace	R-11	R-7	4400	1	4400

[a] All air-conditioning systems were of the packaged-single-zone air-cooled type, except for the Hospital which was modeled with a chiller and cooling tower.

[b] The residential sloped roof area was 1722 ft^2. The commercial roofs were flat.

or modified albedo, as described below. The residential roof was modeled with a two-piece sloped (20°) construction and the commercial as a flat single-piece construction.

DOE-2 building energy simulations were completed for each building type and location for two cases: base roof albedo and modified. The base case was applied to both residences and commercial buildings, which was determined to be 0.25 from analysis of aerial photographs, as discussed in *Chapter 2* and *Appendix A*. It was defined as the average albedo of the surveyed roof population, a distribution of dark and light roofs.

The modified roof albedo case was based on laboratory tested light-colored roofing materials, which differed for low-slope residential and flat-roof commercial applications. Several recently developed white roof coatings for low-slope residential application have measured albedos of 0.51-0.58, see *Attachment 1*. White polymer roof coatings for flat-roof commercial applications are available in the market with a fresh, clean albedo of 0.79, dirty of 0.59-0.61, and washed of 0.64-0.76 (Bretz and Akbari, 1994). Based on these data the modified roof albedos selected were 0.55 for low-sloped residential and 0.70 for flat-roof commercial buildings. Therefore, changes in roof albedo were 0.30 for residences and 0.45 for commercial buildings.

Electricity and Gas Prices

The Energy Information Agency (EIA) was the source for residential and commercial energy prices. These were the average 1993 price of electricity (EIA, 1993a) for each utility serving its respective metropolitan area and the state-wide average price of natural gas (EIA, 1993b). They were used to calculate the annual price of energy paid by each building in each metropolitan area and are shown in **Table B-2**. Note, peak demand was not included in the price of electricity.

DOE-2 Simulated HVAC Electricity, Natural Gas, and Net Energy Base Use

Examples of DOE-2 simulated HVAC annual electricity, natural gas, net energy, and peak demand for the base case are presented in **Table 3-2** for residential, office, and retail store buildings in the Los Angeles, Miami, and Phoenix MSAs. DOE-2 results for all building types and MSAs are presented in **Table B-19**. The building peak demand was non-coincident with local utility demand, and the time it occurred varied by building, location, and roof albedo. The net energy dollars for the base and modified cases for both fuel types are shown in **Table 3-3**. The table illustrates the relatively large impact on electricity dollar savings compared to gas deficit dollars.

DOE-2 Simulated HVAC Electricity, Natural Gas, and Net Energy Savings

DOE-2 simulated HVAC energy and monetary savings were calculated as the difference between the modified case relative to the base. Examples are presented in Table 3-2, per $1000ft^2$ flat roof area, and for all buildings and locations in Table B-19. The savings were applicable to single-story buildings or the top floor of multi-story buildings, since only the top floor would realize the benefit of a reduced cooling load.

Table 3-2(a). DOE-2 simulated HVAC base use and savings from light-colored roofing for single-story residences; annual electricity and net energy, peak electricity demand, and annual natural gas are estimated **per 1000ft^2 of flat roof area.**

single-story residential												
Metropolitan Area	Old w/ Gas Furnace			Old w/ Heat Pump			New w/ Gas Furnace			New w/ Heat Pump		
	Base Case	Savings		Base Case	Savings		Base Case	Savings		Base Case	Savings	
		Δ	%		Δ	%		Δ	%		Δ	%
Los Angeles												
Electricity (kWh/1000ft^2)	1364	238	17	2588	177	7	846	126	15	1349	101	7
Gas (kBtu/1000ft^2)	10721	-544	-5	0	0	0	5375	-244	-5	0	0	0
Net Energy ($/1000ft^2)	200	20	10	254	18	7	116	11	9	132	10	8
Peak (W/1000ft^2)	2305	247	11	2305	247	11	1481	130	9	1481	130	9
Miami												
Electricity (kWh/1000ft^2)	5150	376	7	5277	374	7	3689	205	6	3734	205	5
Gas (kBtu/1000ft^2)	1086	-20	-2	0	0	0	457	-1	0	0	0	0
Net Energy ($/1000ft^2)	428	30	7	427	30	7	303	16	5	303	17	6
Peak (W/1000ft^2)	2409	208	9	2409	208	9	1545	84	5	1545	84	5
Phoenix												
Electricity (kWh/1000ft^2)	5495	484	9	6643	459	7	3590	256	7	4102	247	6
Gas (kBtu/1000ft^2)	9388	-211	-2	0	0	0	4816	-90	-2	0	0	0
Net Energy ($/1000ft^2)	656	51	8	711	49	7	419	27	6	439	27	6
Peak (W/1000ft^2)	4123	162	4	4123	162	4	2656	97	4	2656	97	4

Table 3-2(b). DOE-2 simulated HVAC base use and savings from light-colored roofing for single-story offices; annual electricity and net energy, peak electricity demand, and annual natural gas are estimated **per 1000ft^2 of flat roof area.**

	single-story office											
	Old w/ Gas Furnace			Old w/ Heat Pump			New w/ Gas Furnace			New w/ Heat Pump		
Metropolitan Area	Base Case	Savings		Base Case	Savings		Base Case	Savings		Base Case	Savings	
		Δ	%		Δ	%		Δ	%		Δ	%
Los Angeles												
Electricity (kWh/1000ft^2)	4174	377	9	4293	341	8	3271	221	7	3301	215	7
Natural Gas (kBtu/1000ft^2)	878	-306	-35	0	0	0	224	-82	-37	0	0	0
Net Energy (\$/1000ft^2)	377	32	8	382	30	8	292	19	7	294	19	6
Peak (W/1000ft^2)	3914	292	7	3914	292	7	2886	173	6	2886	173	6
Miami												
Electricity (kWh/1000ft^2)	8664	424	5	8670	418	5	6536	239	4	6536	233	4
Natural Gas (kBtu/1000ft^2)	61	0	0	0	0	0	0	0	0	0	0	0
Net Energy (\$/1000ft^2)	590	29	5	590	28	5	444	16	4	444	16	4
Peak (W/1000ft^2)	4482	153	3	4482	153	3	3208	57	2	3208	57	2
Phoenix												
Electricity (kWh/1000ft^2)	8030	562	7	8192	538	7	5848	305	5	5890	293	5
Natural Gas (kBtu/1000ft^2)	1000	-265	-26	0	0	0	286	-82	-29	0	0	0
Net Energy (\$/1000ft^2)	744	50	7	754	50	7	539	28	5	542	27	5
Peak (W/1000ft^2)	5857	196	3	5857	196	3	4065	96	2	4065	96	2

Table 3-2(c). DOE-2 simulated HVAC base use and savings from light-colored roofing for single-story retail stores; annual electricity and net energy, peak electricity demand, and annual natural gas are estimated **per 1000ft^2 of flat roof area.**

single-story retail store												
Metropolitan Area	Old w/ Gas Furnace			Old w/ Heat Pump			New w/ Gas Furnace			New w/ Heat Pump		
	Base Case	Savings		Base Case	Savings		Base Case	Savings		Base Case	Savings	
		Δ	%		Δ	%		Δ	%		Δ	%
Los Angeles												
Electricity (kWh/1000ft^2)	6026	593	10	6026	593	10	4760	344	7	4760	344	7
Natural Gas (kBtu/1000ft^2)	864	0	0	0	0	0	864	0	0	0	0	0
Net Energy ($/1000ft^2)	541	53	10	536	53	10	429	31	7	424	31	7
Peak (W/1000ft^2)	3352	193	6	3352	193	6	2264	38	2	2264	38	2
Miami												
Electricity (kWh/1000ft^2)	10443	477	5	10443	477	5	7839	260	3	7839	260	3
Natural Gas (kBtu/1000ft^2)	864	0	0	0	0	0	864	0	0	0	0	0
Net Energy ($/1000ft^2)	715	32	4	710	32	5	538	18	3	533	18	3
Peak (W/1000ft^2)	3270	131	4	3270	131	4	2374	70	3	2374	70	3
Phoenix												
Electricity (kWh/1000ft^2)	10497	716	7	10497	716	7	7567	416	5	7567	416	5
Natural Gas (kBtu/1000ft^2)	864	0	0	0	0	0	864	0	0	0	0	0
Net Energy ($/1000ft^2)	970	66	7	966	66	7	701	38	5	696	38	5
Peak (W/1000ft^2)	4748	112	2	4748	112	2	3219	91	3	3219	91	3

Table 3-3. DOE-2 simulated HVAC base and modified case annual energy cost estimates for single-story buildings modeled with gas furnace heating expressed in **dollars per 1000ft^2 of flat roof area.**

metropolitan area	roof color	type	residence		office		retail store	
			old	new	old	new	old	new
Los Angeles	dark (base)	electricity	134	83	371	291	536	424
		natural gas	66	33	5	1	5	5
	light (modified)	electricity	110	71	338	271	484	393
		natural gas	70	35	7	2	5	5
Miami	dark (base)	electricity	417	299	589	444	710	533
		natural gas	11	5	0	0	5	5
	light (modified)	electricity	387	282	560	428	678	515
		natural gas	11	5	0	0	5	5
Phoenix	dark (base)	electricity	588	384	739	538	966	696
		natural gas	68	34	5	1	4	4
	light (modified)	electricity	536	356	687	510	900	658
		natural gas	69	35	7	2	4	4

The annual cooling electricity savings ranged from 100 to 480 kWh per 1000ft^2 of flat roof area (7 to 17%) for old residential buildings, 40 to 260 kWh per 1000ft^2 of flat roof area (6 to 15%) for new residences, 170 to 560 kWh per 1000ft^2 of flat roof area (5 to 9%) for old offices, 100 to 310 kWh per 1000ft^2 of flat roof area (3 to 7%) for new offices, 240 to 720 kWh per 1000ft^2 of flat roof area (5 to 10%) for old retail stores, and 130 to 420 kWh per 1000ft^2 flat roof area (3 to 7%) for new retail stores, all with gas furnace heating. The relative savings were most significant in the shell dominated residential prototypes, as the others were internal load dominated. These six building types accounted for 93% of the total conditioned flat roof area of the 11 MSAs.

Prototypes with gas heating systems had annual electricity and net energy savings greater than those with electric heat pumps, because of the higher cost of electric heat relative to gas. The residential, office, and retail store old vintage prototypes had relatively greater savings than those of the new vintage, primarily because of the roof insulation R-value differential. Prototypes with longer hours of operation showed relatively larger savings with respect to those with shortened schedules. For example, the hospital and nursing home prototypes operate continuously and had the largest savings in annual electricity, which were 455 to 1687 kWh per 1000ft^2 of flat roof area (3 to 8%) for the hospital and 183 to 1071 kWh per 1000ft^2 of flat roof area (5 to 11%) for the nursing home. These were followed in order by retail stores, the grocery store, offices, residences, and schools. Peak electricity demand savings were observed in all prototypes and locations, however they exhibited random behavior since the system sizes were pre-set and peak loads were not always met.

The few prototypes with annual electricity and net energy deficits or savings very close to zero were found in Chicago and Philadelphia among the new vintage, electric heat pump office models, and additionally for residences in New York City. The new vintage, gas furnace heated residence for Philadelphia also operated at a net energy deficit.

DOE-2 Simulated HVAC Electricity, Natural Gas, and Net Energy Savings by Climate

We plotted HVAC electricity, net energy, and peak savings versus cooling degree hours and gas deficit versus heating degree hours to exhibit trends between these variables. These are shown in **Figures B-1** through **B-4** for all building types. Generally, annual electricity and net energy savings increased with cooling degree hours and natural gas deficit increased with heating degree hours. Peak electricity demand savings indicated no correlation with cooling degree hours, since the system sizes were fixed and the peak cooling demands were not always met. **Figure 3-1** illustrates the relationship between increasing net energy savings and increasing cooling degree hours for old and new residences, offices, and retail stores, all with gas furnace heating. Los Angeles and Phoenix exhibit greater savings than the trend because of a high solar radiation fraction (low sky cover) relative to the other locations, see Table B-1. These trends can provide a means to determine at which locations and to what degree light-colored roofing is cost-effective.

Linearity Property

The annual electricity and net energy savings, peak electricity demand savings, and annual natural gas deficit were found to be a linear function of changes in roof albedo for each building type and location. This was observed in a previous Lawrence Berkeley National Laboratory (LBNL) research study of residential and office buildings in the Los Angeles Basin, which is documented in *Attachment 2* and referred to as the 'linearity property'. Essentially, the linearity property allows for energy and monetary savings presented here to be adjusted for applications where the base and/or modified rooftop albedo differ from our assumptions. In *Chapter 5* we make use of this property, since the base albedo varies with location.

The savings presented in this chapter are based on a change in albedo ($\Delta a1$) of 0.30 for residences and 0.45 for commercial buildings. For example, the residential savings would increase 67% if the base case were represented by a new black asphalt shingle with an albedo of 0.05 (in place of 0.25) and the modified case remained at 0.55 ($\Delta a1 = 0.30$ and $\Delta a2 = 0.50$).

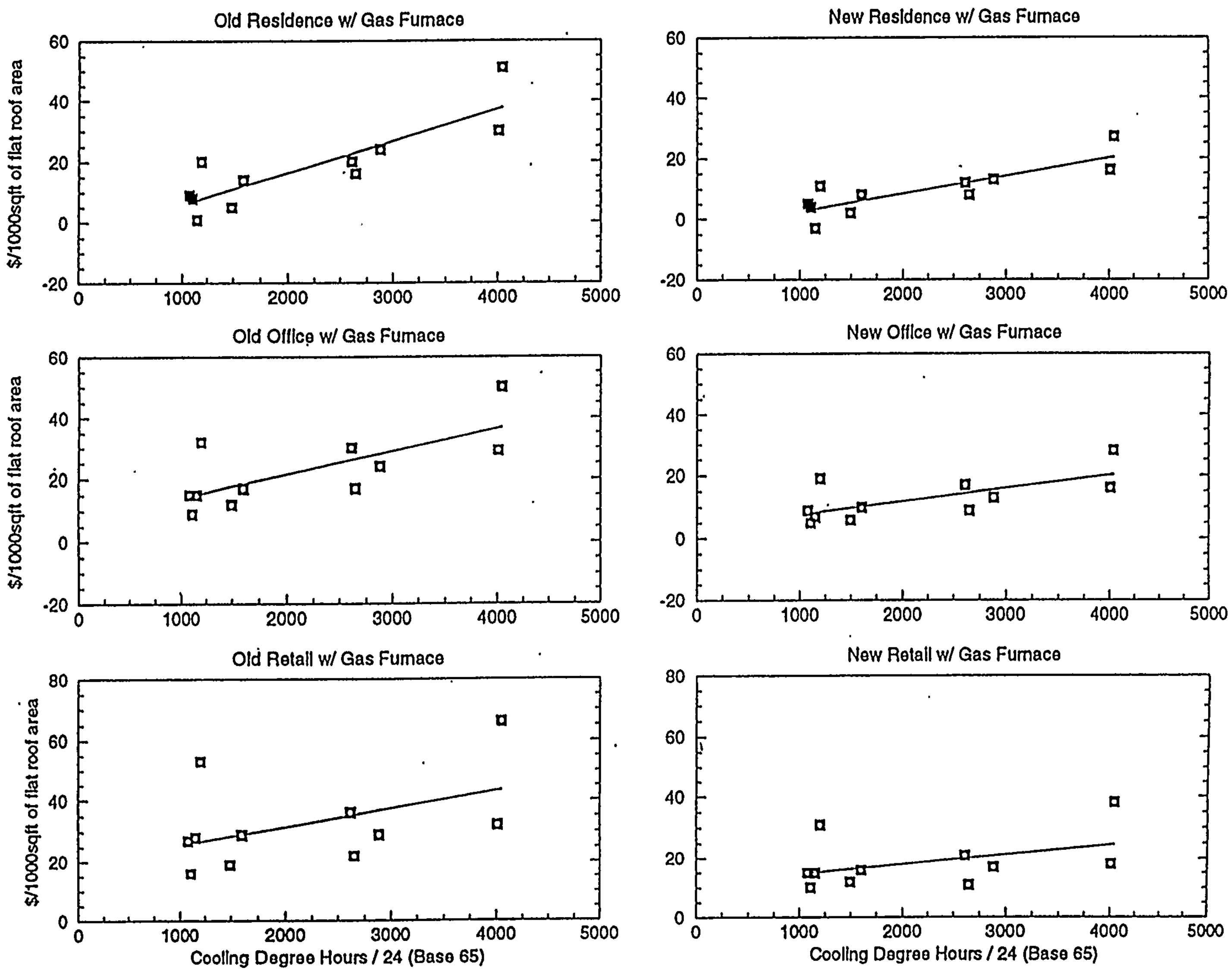

Figure 3-1. DOE-2 simulated HVAC annual net energy savings from light-colored roofing for single-story old and new residences, offices, and retail stores, all with gas furnace heating. The figure illustrates the relationship between increasing net energy savings and increasing cooling degree hours.

Discussion

We believe the savings predicted with DOE-2 were under-estimated for the following five reasons. First, the DOE-2 simulations do not include the recently developed LBNL roof/attic model[4] that better simulates the roof/attic heat transfer mechanism in DOE-2 (Gartland, et al., 1996). This model incorporates radiative heat transfer, an improved external convection coefficient, and insulation temperature-dependent conductivity, which collectively increase the heat transfer through the roof[5]. Second, the roof composite model does not include a framing factor, which accounts for joists, recessed cans, electrical junction boxes, access doors, and insulation voids, etc, and would increase heat transfer through the structure. Third, the roof modeling neglects the losses to the thermal distribution system in the attic, which under-predicts peak air-conditioning load during summer operation. Fourth, the simulations do not include the effect of snow; i.e., high-albedo material on the roof, which renders the actual roof color irrelevant during the winter in areas with snow fall. Hence, the heating penalty estimated from a light-colored roof is currently being paid in cold and snowy areas and would incur no additional penalty. Fifth, the net energy savings estimates do not include savings in peak electricity demand charges. Another consideration is that DOE-2 does not perform thermal comfort calculations. In residences without air conditioning a light-colored roof will lower the mean radiant temperature of the roof and provide for a more comfortable indoor environment.

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[4] The roof/attic model functioned only with single-zone buildings with single-construction flat roofs. Therefore, it could not be applied to our buildings, since the residences were modeled with two-piece sloped roofs and the commercial buildings with multiple zones.

[5] Gartland compared her model with measured hourly air-conditioning electricity use of a school bungalow in Sacramento, California, which initially had a brown roof and was later coated white. The model correctly predicted the annual HVAC electricity savings from the brown and white-coated roofs, which were previously under-estimated by 38-50% without the model.

Chapter 4

Building Stock and Roof Area

Residential

Conditioned flat roof area was estimated for both residential and commercial buildings. Data for residential building stock came from the American Housing Survey (Source: AHS), a detailed study of housing in cities across the United States[6]. AHS data used were, the number of residences (*N*), the average square footage of each residence (*AREA*), the average number of floors (*FLR*), and the saturation (*SAT*) of natural gas heating, electric heat pumps, and central air conditioning in each MSA. These data were extracted for two vintage categories, houses built before 1980 (old) and those built from 1980 to 1990 (new), and are displayed in **Tables C-1** and **C3**. They were used to find residential conditioned flat roof area (*ROOF AREA*) as in equation [1], which is displayed in **Table 4-1**, and in more detail, with saturations, in Table C-3.

$$ROOF\ AREA = \frac{N \times AREA}{FLR} \times SAT \qquad [1]$$

Commercial

Commercial building stock data were collected from the Commercial Building Energy Consumption Survey (CBECS, 1994). CBECS divided the U.S. into 9 census divisions. Unfortunately, the commercial data was not disaggregated further into MSAs within each region. We assumed that building stock in each census division were distributed proportionally to population. For example, a city like Atlanta with 6.9% of the South Atlantic census division's population, was assumed to contain 6.9% of the South Atlantic division's commercial building stock. The population of each CBECS census division is listed in **Table C-2**.

CBECS divided commercial buildings into 21 principal building activities. For this study, the principle building activities were reduced to seven (office, retail store, primary and secondary schools, hospital, nursing home, and grocery store) with the remainder neglected. We divided the office and retail store CBECS data for each census division into two categories based on the year of the buildings' construction, built either before 1980 (old) or during 1980 or later (new). We assumed the characteristics for each of these building types to be uniform throughout each census division. Therefore, the building characteristics in Atlanta, such as the total floor area (*AREA*), number of floors (*FLR*), and HVAC system saturations (*SAT*), were assumed to be the same as the building characteristics in the South Atlantic census division. These characteristics were used to find commercial conditioned flat roof area (*ROOF AREA*) as in equation [2], which is displayed in Table 4-1, and in more detail, with saturations, in Table C-3.

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[6] All data contained in the AHS were adjusted to cover housing built in the years up to and including 1990.

$$ROOF\ AREA = \frac{AREA}{FLR} \times SAT \qquad [2]$$

The Mountain and Pacific census divisions cover very large and varied terrain. To better represent Phoenix and Los Angeles we split these two divisions based on the number of heating degree days (65°F). The Mountain region was split into "north" for heating degree days greater than 5500, and "south" for the remainder. Phoenix fell into the "south" Mountain region. The Pacific region was split into "north" for heating degree days greater than 4000, and "south" for the remainder, which included Los Angeles.

Summary

The old residence accounted for 51% of the total conditioned flat roof area of 12.9 Bft^2, and the total residential representation was 76%, offices added 8%, and retail stores 9%. These six building types accounted for 93% of the total conditioned flat roof area of the 11 MSAs.

Table 4-1. Conditioned flat roof area of residential and commercial building stock.

metropolitan area	conditioned flat roof area (Mft^2)		
	residential	commercial	total
Atlanta	818	92	910
Chicago	765	368	1133
Los Angeles	1152	598	1750
Dallas/Fort Worth	1452	317	1769
Houston	1228	303	1530
Miami/Fort Lauderdale	855	103	958
New Orleans	422	115	537
New York	338	621	959
Philadelphia	542	203	745
Phoenix	952	142	1093
DC/Baltimore	1326	204	1531
Total	9850	3066	12915

building type	conditioned flat roof area (Mft^2)
Residence Old	6630
Residence New	3219
Office Old	637
Office New	334
Retail Store Old	859
Retail Store New	292
School	708
Hospital	68
Nursing Home	89
Grocery Store	79
Total	12915

Chapter 5

Metropolitan-Scale and National HVAC Energy and Monetary Savings

Savings in Eleven Metropolitan Statistical Areas

Metropolitan-scale HVAC annual electricity and net energy savings, peak electricity demand savings, and annual natural gas deficit were estimated by taking the product of the building-scale energy and monetary savings (Table B-19), the conditioned flat roof area (Table C-3), and the ratio of the local change in albedo to the change our simulations are based on. The savings are displayed in **Table D-1**. Below are examples of metropolitan-scale electricity savings for residential and office buildings in the South (Los Angeles) and North (Chicago).

- Example 1: In Los Angeles, single-story, old vintage residences with air conditioning and gas furnace heating (conditioned flat roof area of 954 Mft^2) saved 238 $\text{kWh}/1000\text{ft}^2$ of electricity for each residence. They had a local base albedo of 0.30 ($\Delta a = 0.25$) instead of 0.25 ($\Delta a = 0.30$). This resulted in a modified total electricity savings of 189 MWh for these residences in Los Angeles.
- Example 2: In Los Angeles, single-story, old vintage office buildings with air conditioning and gas furnace heating (conditioned flat roof area of 144 Mft^2) saved 377 $\text{kWh}/1000\text{ft}^2$ of electricity for each office. They had a local base albedo of 0.32 ($\Delta a = 0.38$) instead of 0.25 ($\Delta a = 0.45$). This resulted in a modified total electricity savings of 45 MWh for these office buildings in Los Angeles.
- Example 3: In Chicago, single-story, old vintage residences with air conditioning and gas furnace heating (conditioned flat roof area of 545 Mft^2) saved 131 $\text{kWh}/1000\text{ft}^2$ of electricity for each residence. They had a local base albedo of 0.20 ($\Delta a = 0.35$) instead of 0.25 ($\Delta a = 0.30$). This resulted in a modified total electricity savings of 83 MWh for these residences in Chicago.
- Example 4: In Chicago, single-story, old vintage office buildings with air conditioning and gas furnace heating (conditioned flat roof area of 84 Mft^2) saved 191 $\text{kWh}/1000\text{ft}^2$ of electricity for each office. They had a local base albedo of 0.18 ($\Delta a = 0.52$) instead of 0.25 ($\Delta a = 0.45$). This resulted in a modified total electricity savings of 19 MWh for these office buildings in Chicago.

The annual cooling electricity savings in gigawatt hour (GWh), annual natural gas deficit in giga-Btu (GBtu), annual net energy savings in million dollar ($M), and peak electricity demand savings in megawatt (MW) for all 11 MSA are shown in **Table 5-1**. The same quantities per 1000ft^2 roof area of air-conditioned buildings for each MSA are shown in **Table 5-2**. To illustrate the climate effect, the results are plotted in **Figures 5-1** to **5-4**, superimposed on a map of the United States with contours of annual cooling hours for a typical residential building. The data per

$1000ft^2$ of roof area reflect the effects of climate, whereas the MSA savings are strongly affected by the sizes of the populations.

The largest potential for annual net energy savings was found for Phoenix ($37M), followed by Los Angeles ($35M), Houston ($27M), Miami/Fort Lauderdale ($20M), Dallas/Fort Worth ($20M), New York ($16M), Chicago ($10M), New Orleans ($9M), Atlanta ($9M), Washington DC/Baltimore ($8M), and Philadelphia ($3M).

For an entire MSA, savings depend on a combination of factors: in warmer areas there are larger savings per ft^2 and higher saturation of air-conditioned buildings, these are multiplied by the populations. For example, a lower saturation of air conditioning and a lower magnitude of cooling energy use per ft^2 of air-conditioned buildings are the reasons that the energy savings in Los Angeles are less than in Phoenix, despite its being 7 times more populous. Another factor of about 30% is introduced by the variation of roof albedos from north to south among the MSAs. Roofs in the North seem to be darker, which increases the opportunity for savings there. Another factor that affects the results for monetary savings is the local cost of electricity. The high price of electricity in New York ($0.16/kWh) compared to Atlanta or New Orleans ($0.08/kWh) causes the dollar savings in New York to be almost twice as much as Atlanta.

The annual electricity savings, annual natural gas deficit, annual net energy savings, and peak electricity demand savings totaled for all 11 MSA were 2.6 tera-watt hours (TWh) (200 kilo-watt hours per $1000ft^2$ roof area of air-conditioned buildings), 6.9 TBtu (5 therms per $1000ft^2$), $194 million ($15 per $1000ft^2$), 1.7 GW (135 W per $1000ft^2$), respectively.

Six building types accounted for over 90% of the annual electricity and net energy savings: old residences were responsible for almost 55%, new residences 15%, and four other building types (old/new offices and old/new retail stores) together almost 25%.

National Savings

The results for the 11 MSAs were extrapolated to estimate the savings in the entire United States. This extrapolation was done in two different ways, first by accounting for the climatic variations of the savings and second by scaling to the national population. The details of the climatic extrapolation method are discussed in *Appendix E.*

The climatic zone extrapolation is considered first. The MSAs were located in three climatically distinct zones as defined in the Residential Energy Consumption Survey (RECS, 1995). The hottest zone (5) contained the following MSAs: Phoenix, New Orleans, Houston, Dallas/Fort Worth, and Miami/Fort Lauderdale; zone (4): Atlanta and Los Angeles; and zone 3: Chicago, New York City, Philadelphia, and DC/Baltimore. Naturally, most of the savings were found in the hottest zone (5). These are shown in **Table 5-3**. This resulted in annual electricity savings of 11.1 TWh, (56% in zone 5, 22% in zone 3, and 22% in zone 3), annual net energy savings of

$850M, (63% in zone 5, 21% in zone 3, and 16% in zone 3), an annual gas deficit of 28.2 TBtu, and peak electricity demand savings of 7.2 GW.

National estimates were also derived from scaling by population, where the 1990 population of the 11 MSA was 70 million and the entire United States was 249 million. The savings estimates from the 11 MSA were increased by the ratio of 249 to 70 (3.56) and are shown in Table 5-3. This resulted in a reduction of 9.3 TWh in annual electricity use, $680M in annual net energy payments, and 6.2 GW in peak electricity demand. The associated heating penalty was 24.5 TBtu. The reduction in peak electricity demand is the equivalent of 12 to 14 power plants each of 0.5 GW capacity.

Table 5-1. Estimates of **metropolitan-scale** annual direct cooling electricity savings, annual natural gas penalty, net dollar savings, and peak electricity demand savings, resulting from application of light-colored roofing on residential and commercial buildings in 11 Metropolitan Statistical Areas. Net dollar savings are calculated using the local cost of electricity and gas. For example, in Phoenix, the average price of electricity and gas for commercial and residential consumers are: 1kWh costs $0.104; and 1MBtu $6.40.

Metropolitan Area	Residential Savings						Commercial Savings						Residential and Commercial Savings					
	elec		gas		**net**	peak	elec		gas		**net**	peak	elec		gas		**net**	peak
	(GWh)	(M$)	(GBtu)	(M$)	**(M$)**	(MW)	(GWh)	(M$)	(GBtu)	(M$)	**(M$)**	(MW)	(GWh)	(M$)	(GBtu)	(M$)	**(M$)**	(MW)
Atlanta	125	9.8	-349	-2.4	**7.4**	83	22	1.6	-55	-0.3	**1.3**	14	147	11.4	-404	-2.7	**8.7**	97
Chicago	100	11.2	-988	-5.4	**5.8**	89	84	7.0	-535	-2.7	**4.3**	56	183	18.2	-1523	-8.1	**10.1**	145
Los Angeles	210	20.6	-471	-2.9	**17.7**	218	209	18.6	-154	-0.9	**17.7**	102	419	39.2	-625	-3.8	**35.4**	320
Dallas / Ft Worth	241	18.6	-479	-2.8	**15.8**	175	71	4.5	-113	-0.5	**4.0**	36	312	23.1	-592	-3.3	**19.8**	211
Houston	243	22.6	-284	-1.7	**20.9**	127	79	6.0	-62	-0.3	**5.7**	30	322	28.6	-347	-2.0	**26.6**	156
Miami / Ft Lauderdale	221	17.9	-4	0.0	**17.9**	115	35	2.4	-3	0.0	**2.4**	11	256	20.3	-7	0.0	**20.3**	125
New Orleans	84	6.6	-107	-0.7	**5.9**	27	33	2.8	-28	-0.1	**2.7**	16	117	9.4	-135	-0.8	**8.6**	42
New York	35	5.6	-331	-2.7	**2.9**	56	131	16.5	-540	-3.3	**13.2**	95	166	22.1	-871	-6.0	**16.1**	151
Philadelphia	44	5.6	-954	-6.5	**-0.9**	108	47	5.5	-292	-1.8	**3.7**	49	91	11.1	-1246	-8.3	**2.8**	157
Phoenix	299	32.0	-74	-0.5	**31.5**	106	58	5.3	-31	-0.2	**5.1**	18	357	37.3	-105	-0.7	**36.6**	123
DC / Baltimore	182	13.1	-845	-7.0	**6.1**	183	45	3.2	-184	-1.1	**2.1**	31	227	16.3	-1029	-8.1	**8.2**	214
Total	1784	163.6	-4886	-32.6	**131.0**	1287	814	73.4	1997	11.2	**62.2**	458	2597	237.0	6884	43.8	**193.2**	1741

Table 5-2. Estimates of annual direct savings and penalties **per 1000 ft^2 of roof area of air-conditioned buildings** resulting from application of light-colored roofing on residential and commercial buildings in 11 Metropolitan Statistical Areas. Net dollar savings are calculated using the local cost of electricity and gas. For example, in Phoenix, the average price of electricity and gas for commercial and residential consumers are: 1kWh costs \$0.104; and 1 therm = 0.1MBtu costs \$0.64.

Metropolitan Area	Residential Savings				Commercial Savings				Residential and Commercial Savings			
	elec (kWh)	gas (therms)	**net ($)**	peak (W)	elec (kWh)	gas (therms)	**net ($)**	peak (W)	elec (kWh)	gas (therms)	**net ($)**	peak (W)
Atlanta	153	-4	**10**	102	239	-6	**11**	152	162	-4	**10**	107
Chicago	131	-13	**8**	116	228	-15	**11**	152	162	-13	**9**	128
Los Angeles	182	-4	**16**	189	350	-3	**30**	171	239	-4	**20**	183
Dallas / Ft Worth	166	-3	**11**	121	224	-4	**13**	114	176	-3	**11**	119
Houston	198	-2	**17**	103	261	-2	**20**	99	211	-2	**18**	102
Miami / Ft Lauderdale	259	0	**21**	135	340	0	**19**	107	267	0	**21**	131
New Orleans	199	-3	**14**	64	287	-2	**26**	139	218	-3	**17**	78
New York	104	-10	**9**	166	211	-9	**21**	153	173	-9	**17**	158
Philadelphia	81	-18	**-2**	199	232	-14	**20**	241	122	-17	**4**	211
Phoenix	314	-1	**34**	111	409	-2	**35**	127	327	-1	**34**	113
DC / Baltimore	137	-6	**5**	138	221	-9	**10**	152	148	-7	**5**	140

Figure 5-1: Annual Net Dollar Savings for 11 Metropolitan Areas

Net \$ Savings = \$ Cooling Energy Savings – \$ Heating Energy Penalties

The contour map shows simulated annual cooling hours for a typical house (Source: Kelly & Parken 1978).

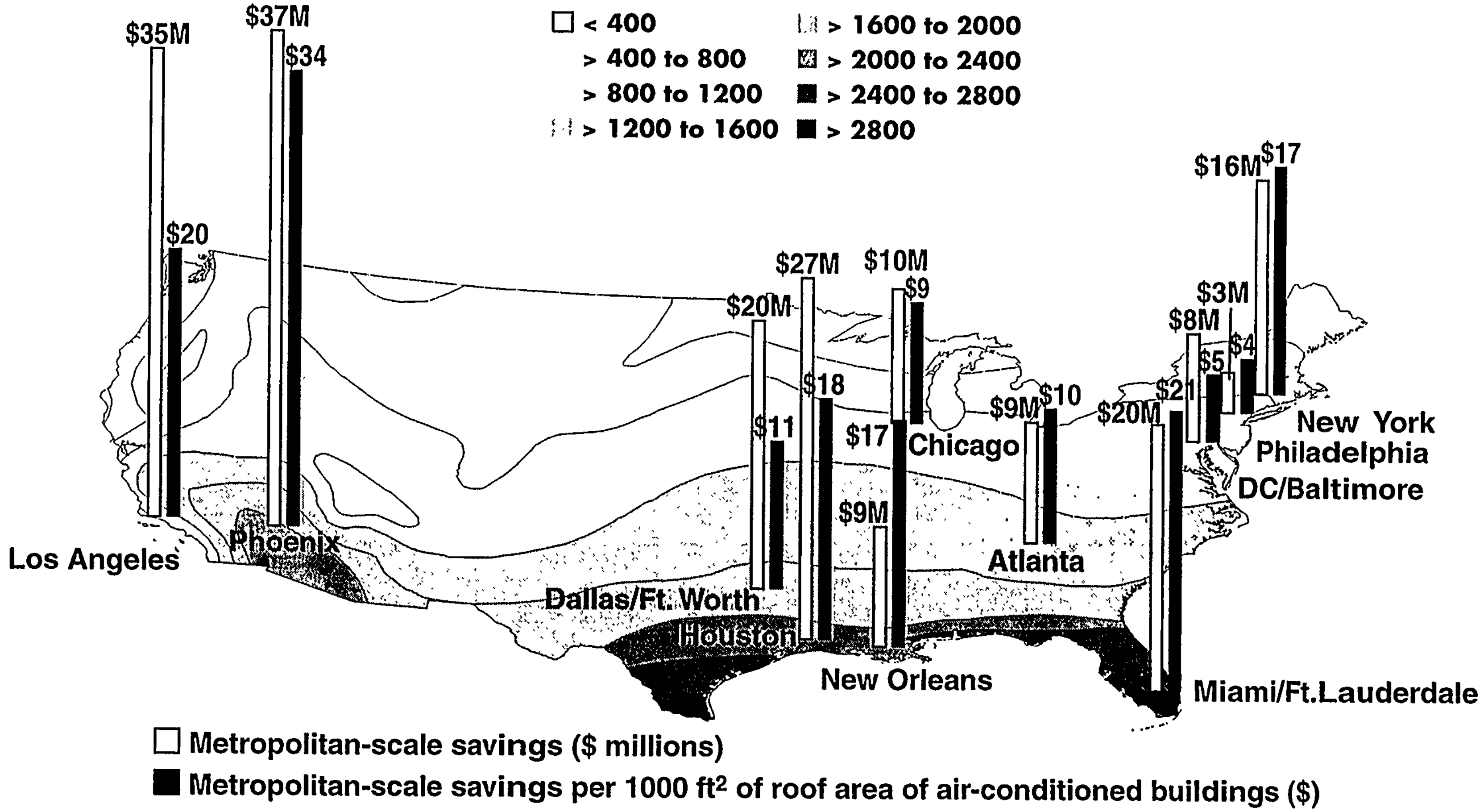

Figure 5-2: Annual Cooling-Electricity Savings for 11 Metropolitan Areas

The contour map shows simulated annual cooling hours for a typical house (Source: Kelly & Parken 1978).

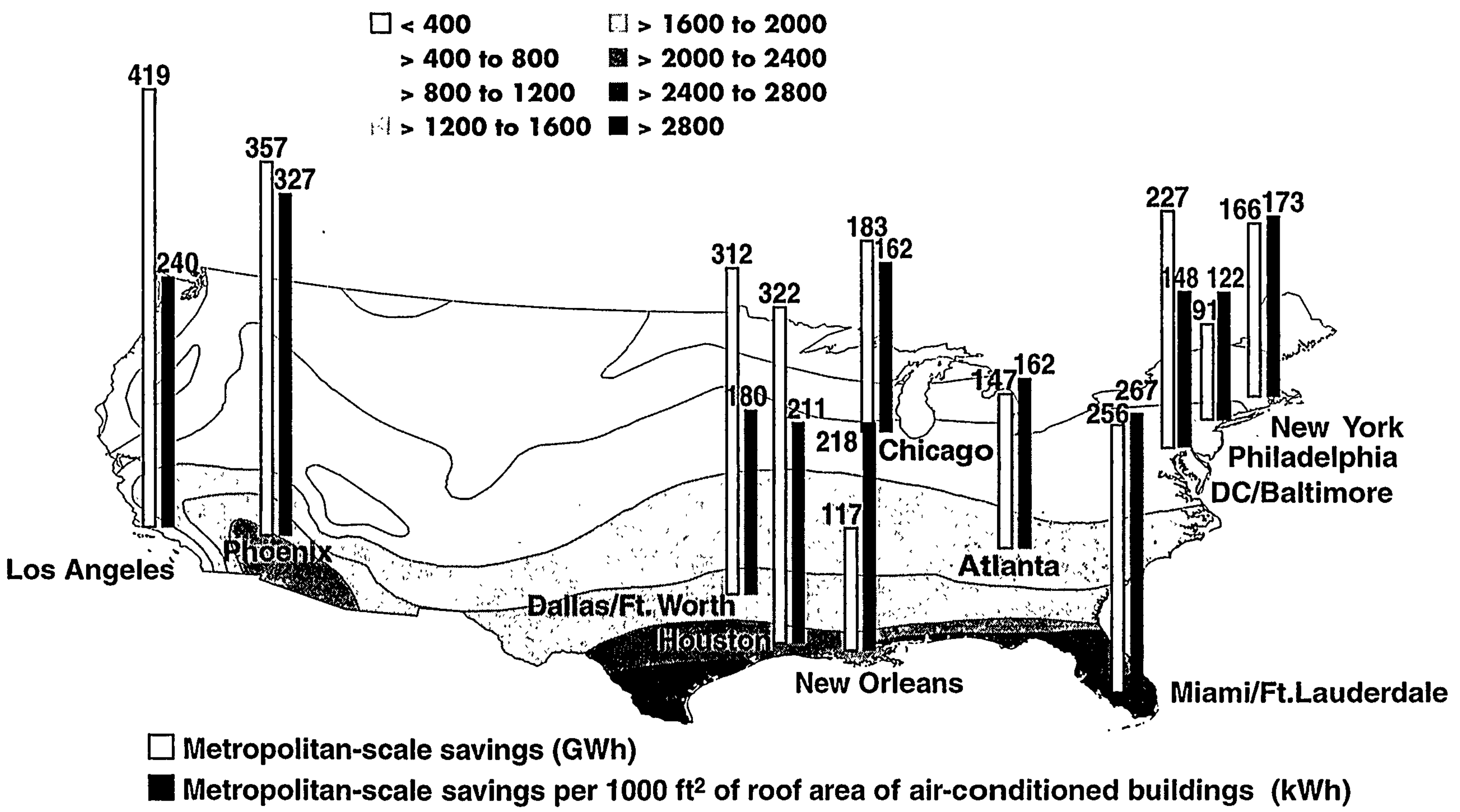

Figure 5-3: Annual Heating Energy Penalties for 11 Metropolitan Areas

The contour map shows simulated annual cooling hours for a typical house (Source: Kelly & Parken 1978).

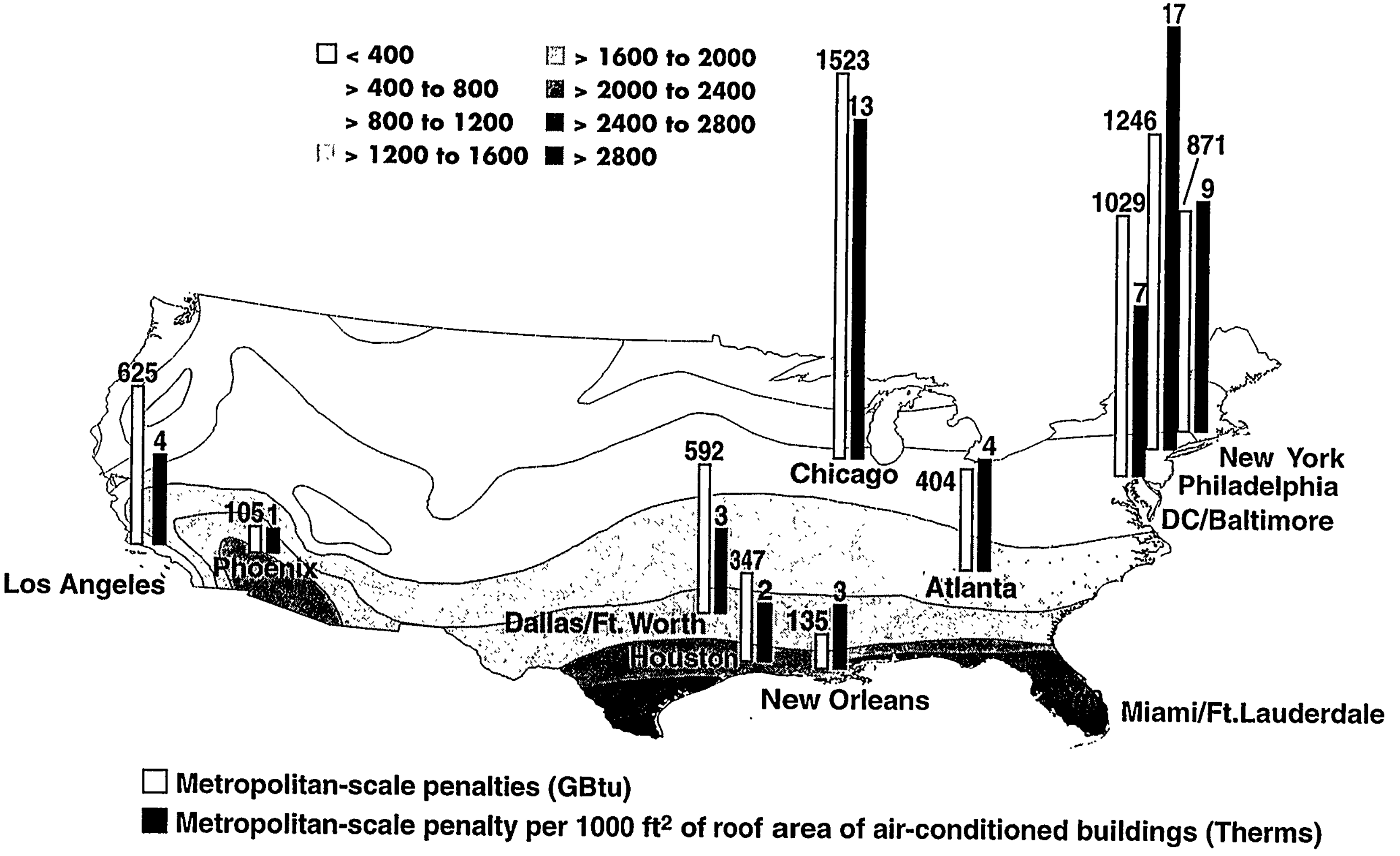

Figure 5-4: Peak-Cooling Electricity Demand Savings for 11 Metropolitan Areas

The contour map shows simulated annual cooling hours for a typical house (Source: Kelly & Parken 1978).

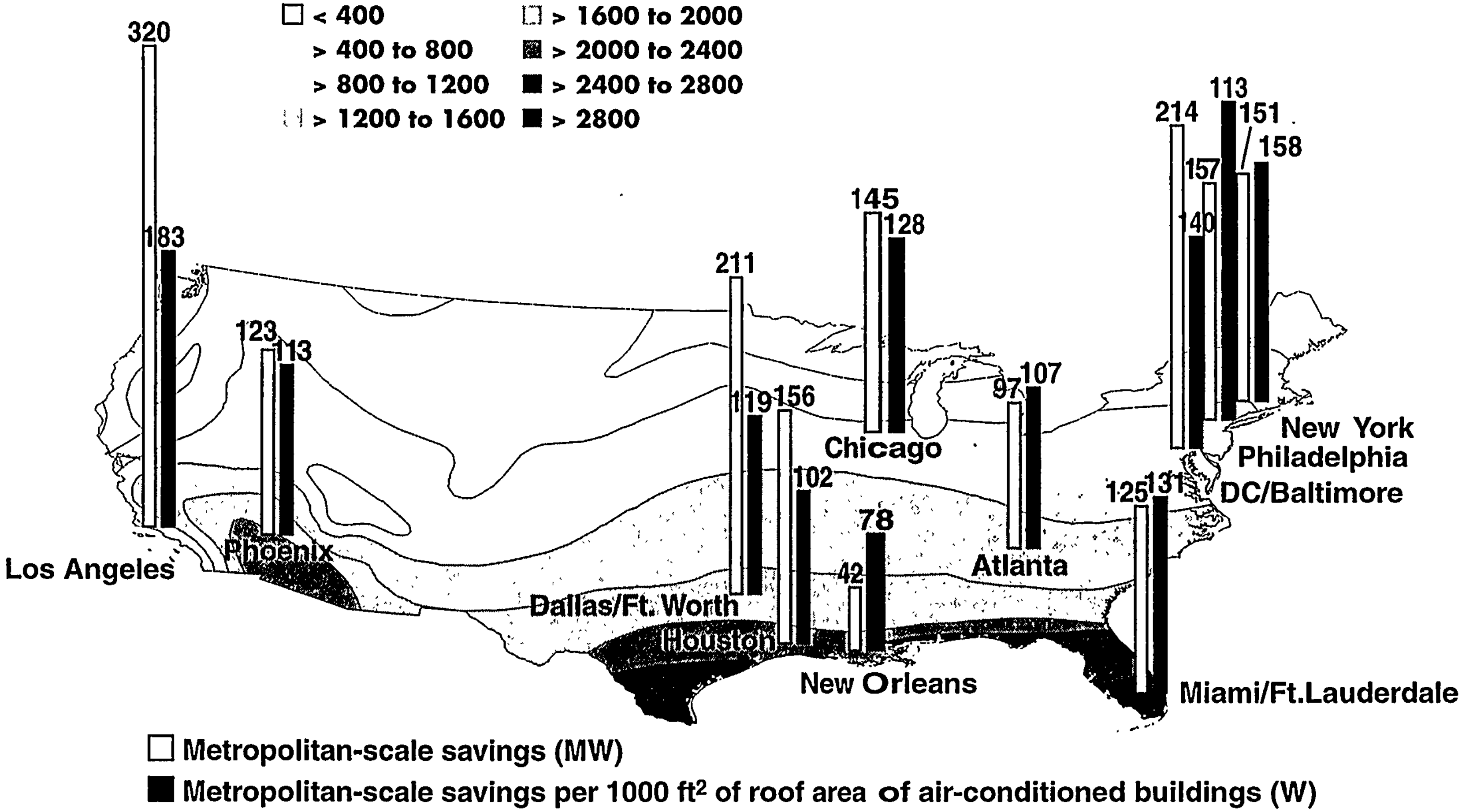

Table 5-3. Potential **national** energy savings resulting from the application of light-colored roofs to residential and commercial buildings.

savings type	extrapolation by	
	climate zone	population
Electricity [TWh]		
Residential	7.7	6.3
Commercial	3.5	2.9
Total	**11.1**	**9.3**
Natural Gas [TBtu]		
Residential	-20.3	-17.4
Commercial	-7.9	-7.1
Total	**-28.2**	**-24.5**
Net Energy [$M]		
Residential	600	460
Commercial	250	210
Total	**850**	**680**
Peak Demand [GW]		
Residential	5.4	4.6
Commercial	1.9	1.6
Total	**7.2**	**6.2**

Chapter 6

Conclusion

This study provides quantitative estimates of the amount of energy and money that lighter-colored roofs can save in the United States. As expected, the largest savings in individual buildings are in the hottest and sunniest cities. In Phoenix, for example, our DOE-2 simulations of an old residence predicted that a whiter roof results in savings of \$51 per year per 1000ft^2 roof area of air-conditioned buildings. In Miami the comparable saving was \$30. The savings decrease as the climate gets cooler, but for most building types, net savings are positive in colder climates as far north as Chicago. Our study includes MSAs in the three warmest climate zones.

For an entire MSA, savings depend on a combination of factors: in warmer areas there are larger savings per ft^2 and higher saturation of air-conditioned buildings, these are multiplied by the populations. For example, a lower saturation of air conditioning and a lower magnitude of cooling energy use per ft^2 of air-conditioned buildings are the reasons that the energy savings in Los Angeles are less than in Phoenix, despite its being 7 times more populous. Another factor of about 30% is introduced by the variation of roof albedos from north to south among the MSAs. Roofs in the North seem to be darker, which increases the opportunity for savings there. Now that we have evidence that savings can be had in the North, whiter roofs can be encouraged there, as well as in the South. Another factor that affects the results for monetary savings is the local cost of electricity. The high price of electricity in New York (\$0.16/kWh) compared to Atlanta or New Orleans (\$0.08/kWh) causes the dollar savings in New York to be almost twice as much as Atlanta.

We have also extrapolated the MSA results to the entire U.S. Scaling according to climate zones shows that if the present roofs were changed to an optimum reflectivity, the savings would be about 750 M\$, and the reduction in peak demand is equivalent to avoiding more than 13 power plants of 0.5 GW capacity. Of these savings, more than half are in the hottest part of the nation, but about 15% could come from the cooler, but populous, northern zone that includes New York and Chicago.

This report is the most comprehensive yet attempted to assess the benefits of cool roofs. There are several ways in which this research could be further advanced. The savings reported here are probably under-estimates because the DOE-2 simulations typically give results less than the savings measured experimentally. Our estimates can be improved as refinements are made in the DOE-2 program.

A simplifying assumption that was made in our analysis is to keep the size of the HVAC system constant, at the size appropriate to the dark roof. As we make the roof cooler, in some cases the cooling load will decrease so much that a smaller air conditioner may suffice to cool the building.

In that case, there could be additional savings because a smaller, less expensive, a/c system might be installed. The smaller system may also handle the load more efficiently, giving continuing savings during use.

An issue that might be addressed in future research is the relative benefits of cooler roofs vs. roof insulation. Calculations, performed in support of standard 90.1 of the American Society for Heating, Refrigeration and Air-Conditioning Engineers (ASHRAE), indicates that use of whiter roofs can substantially reduce the need for roof insulation (Akbari and Konopacki, 1997). Furthermore, an optimum design of roof insulation to account for roof color, can both reduce initial investment in roof insulation and lower the annual energy use of the building.

The results of this research can be used to develop a national plan to implement light-colored roofs. A national plan should initially focus on hot climates (since cool roofs provide significant savings) and flat roof buildings (since materials for cool roofs are currently available in the market). Flat roof buildings are used mostly in commercial buildings as well as some homes. For sloped-roof homes, cool roof materials are mostly at the development stage. Efforts should focus on collaboration with the manufacturers of roofing material for sloped roofs (mostly shingles) to accelerate development and marketing of cool roofs.

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[7] Each location was surveyed every four years on varying 4 year rotations. For example, Chicago was surveyed in 1983, 1987 and 1991, while Phoenix was surveyed in 1981, 1985 and 1989. The most recent survey in publication was used for each of the cities studied in this report, which were: Atlanta, 1991; Chicago, 1991; Fort Worth, 1989; Houston, 1991; Los Angeles, 1985 (the most recent survey, 1989, was not available); Miami, 1990; New Orleans, 1990; New York, 1991; Philadelphia, 1989; Phoenix, 1989; Washington DC, 1993. The bibliographic entry is in a general format and the above cities and dates should be inserted.

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